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Assessment of research needs for sustainability of unconventional machining processes

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Abstract

The use of unconventional machining (UCM) practices is increasing for product manufacture particularly when machining difficult to cut materials and when high precision is required. There is plenty of research conducted on improving sustainability of traditional machining. However, sustainability studies on unconventional/non-traditional machining practices are few. This review aims to determine the current state of the art in sustainability assessment of unconventional machining practices and identify gaps in research. An extensive review was carried out and analysed using a qualitative data analysing software. The analysis shows that only 25 publications directly and indirectly discuss the matter of sustainability of UCM. Out of this almost 70% of publications were recorded after year 2006 showing a clear evidence of uncovered research gap in the field with a growing interest. Despite this trend, evidence on studies which are explicitly dedicated to analyse the sustainability of UCM are rare.

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Keywords: Sustainability; unconventional machining(UCM)

1. Introduction

Manufacturing sector is a vital contributor to the economy of a country. In 2012 manufacturing sector generated €7,000 billion of turnover and employed over 30 million people directly. European industry is a world leader in several manufacturing sectors with mechanical engineering sector having 37% of global market share[1]. The machining processes developed beyond traditional contact based machining are referred as unconventional machining (UCM) in this paper. These processes use electrical, chemical or thermal forms of energy during the material removal process unlike mechanical means in conventional machining. Common example of UCM practices are electrodischarge (EDM), electrochemical machining (ECM), laser beam machining (LBM), electron beam machining and other hybrid machining processes.

The higher the volume of production the amount of resource consumed and emissions to the environment also increases. This has triggered initiatives on sustainability studies of these manufacturing processes. Sustainable development is widely defined as "meeting the needs of the present without compromising the ability of future generations to meet their own needs"[2]. Within this domain, sustainable manufacturing is defined as the "Creation of manufactured products that use processes that minimize negative environmental impacts, conserve energy and natural resources, are safe for employees, communities, and consumers and are economically sound"[3]. The three main pillars of sustainability are environment, economy, and safety. New topics like environmentally benign manufacturing, green manufacturing and sustainable manufacturing have emerged and discussing with increasing popularity.

1.1. Scope and methodology

This study is focused on sustainability implications related to unconventional machining practices. Further, it investigates the available methods for sustainability assessment giving prominence to most widely used UCM techniques. It

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identifies gaps in literature and suggests possible directions of future research.

An extensive review of articles, including journal papers, conference papers, web-based resources and text books was carried out. Literature was thematically coded and analysed using a qualitative data analysis software (NVivo). The content analysis using NVivo (Fig. 1) was used to understand the interrelations, the evolution of studies and the generation of meaningful results in relation to sustainability of machining practices especially with regard to UCM.

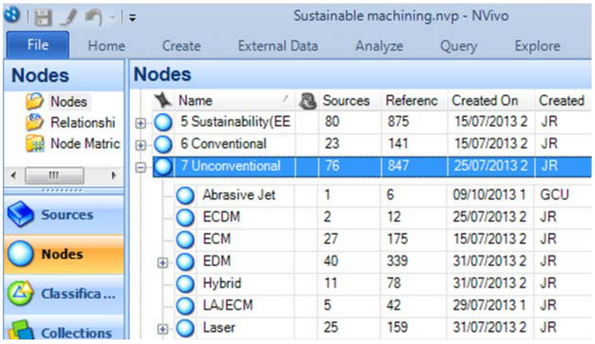

Fig. 1. Content analysis using NVivo

2. Sustainability and unconventional machining (UCM)

The concern for sustainability of manufacturing practices is emphasised highly with recent initiatives by the World trade organisation(WTO) to reward practices that strive to achieve environmental/climate objectives by eliminating tariffs and barriers to trade in 'environmental products/processes"[1]. The initiative has been launched in January 2014 by the EU and fourteen other WTO members including USA and China.

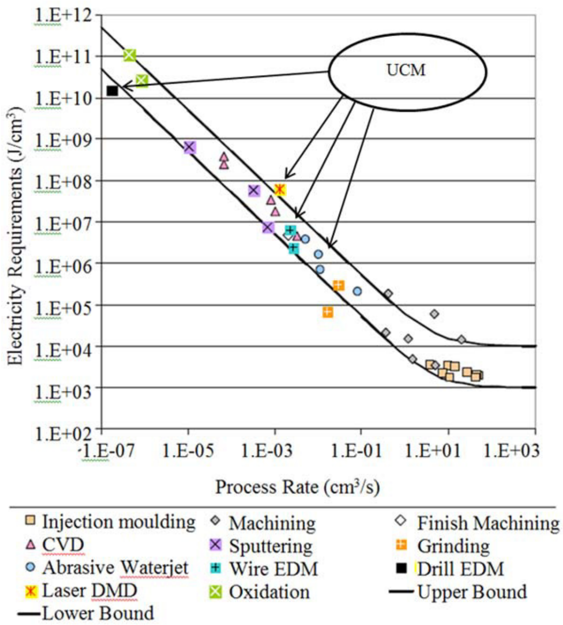

Fig. 2. Electricity requirements for common manufacturing processes[4]

Resource optimisation is a major concern when making manufacturing processes sustainable. An energy consumption study[4] clearly shows that the electricity consumption of unconventional machining processes, especially EDM, are significantly high compared to other manufacturing processes for a given material removal rate as illustrated in Fig. 2. Further, laser and abrasive jet machining show higher energy values compared to conventional machining.

Fig. 3 shows evolution of research on both conventional and unconventional machining related to sustainability over the last 30 year period totaling 120 publications. It is calculated that number of publications after 2010 amounts to 40% of the total reviewed. When compared with the publications in 1990s, the period of year 2000 - 2010 shows a step increase of research publications in the field amounting to an average of 8 publications a year. This has led the amount of papers published after year 2000 to 90% of total. The maximum number of records per year, which is 18 publications, is reported during the year 2011. This indicates a growing interest in sustainability studies of machining techniques.

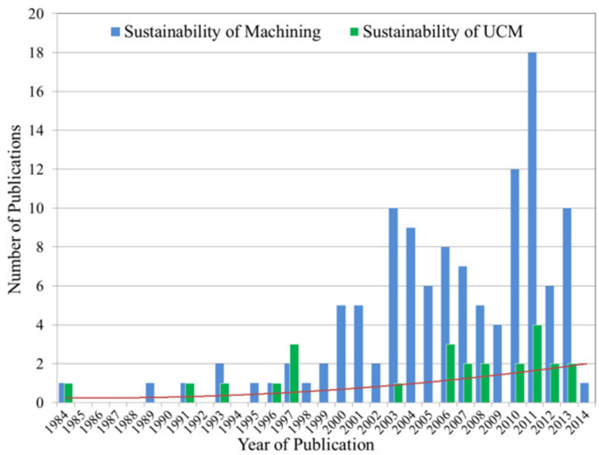

Fig. 3. Distribution of publications on sustainability of machining practices over the years

As depicted in green colour bars in Fig. 3 there are only 25 publications focus on sustainability of unconventional machining during this 30 year span. The earliest study[5] was recorded in 1984, which has investigated water as an alternative dielectric for EDM. Although an explicit environmental impact study was not evident, it was categorised under sustainability considering the environmental benefits of replacing hydrocarbon based dielectrics. Similarly, out of this set of publications many have not discussed the environmental impacts of UCM directly. It can further be noticed that there is only one publication on sustainability of UCM between 1997 till 2006. Almost 70% of publications on UCM (green colour) have been recorded after 2006. This is a strong evidence of identification of the research gap in the field of sustainability of UCM. This might have been encouraged by the increasing awareness of environmental issues of manufacturing and consequent legislative regulations imposed globally.

2.1. Methodologies adopted in previous research on sustainability of UCM

Figure 4 shows the distribution of methodologies adopted in previous studies which discusses sustainability of UCM techniques. The chart is produced based on the only available 25 papers published in the focus area of sustainability of unconventional machining processes.

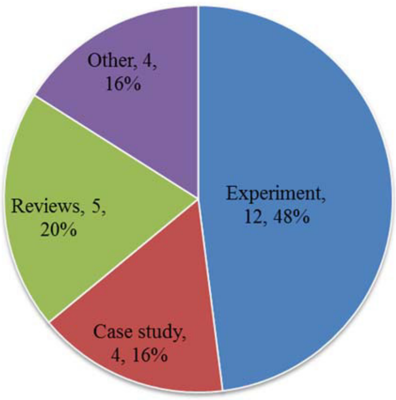

Fig. 4. Methodologies adopted in previous research

It can be seen that almost half (48%) of studies have utilised experimental methods to assess the impact. EDM and laser machining techniques are prominent in this category. Around 1/5th of analyses are based on reviews on academic and industry literature which forms insightful results including the energy analysis in Fig. 2. Case study method has been used only with 4 publications all of which are on laser machining. The balance 16% of publications under the other category comprises surveys, mathematical modelling and other types of analysis methods.

2.2. Electro discharge machining (EDM)

EDM is a process of machining electrically conductive materials by using precisely controlled sparks that occur between an electrode and a workpiece in the presence of a dielectric medium[6]. There are a handful of publications that can be found directly discussing environmental sustainability implications of EDM. A study on environmental assessment on EDM[7] presents a data collection effort to calculate the total environmental impact of three EDM techniques, die sinking EDM, wire EDM and micro EDM. This study[7] has shown that during one hour of EDM roughing operation, the electrical energy for EDM process and the dielectric (hydrocarbon oil) utilised are the main contributors for the total impact amounting to 47.3% and 23.1% respectively Fig. 5. The third highest contributor to the total environmental impact is energy consumed for cooling operation of the machine which amounts to 19.4%. Altogether, energy consumed for EDM process itself (47.3%), process cooling (19.4%) and energy consumed for exhaust system (3.9%) amounts to a total of 70.6% of the total environmental impact.

The balance 29.6% of total environmental impact has caused mainly from dielectric production and disposal, electrode material and workpiece material. Contributions to the environmental impact from lubrication of the machine, compressed air generation and process emissions are less than 1%. However, a later analysis[8] by same authors as in [7] indicates that the dielectric is causing 43.4% of environmental impact during 1 hour of EDM whilst impact from energy amounting to 41%. This concludes that energy and dielectric cause similar burdens on environment during EDM.

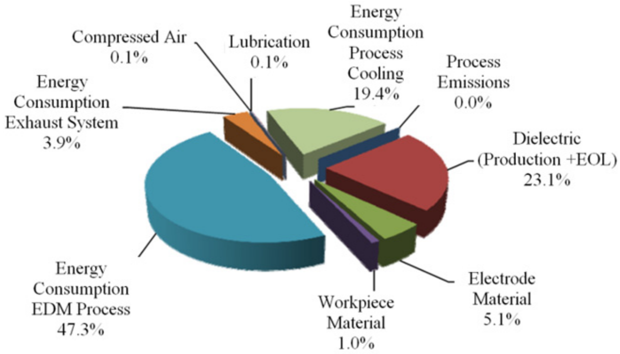

Fig. 5. Distribution of the environmental impact during one hour of EDM roughing (copper electrode, hard metal workpiece) based on the ReCiPe Endpoint (H) V1.04 / Europe ReCiPe H/A method using the ecoinvent v2.0 database and expressed in millipoints (mPts)[7]

Almost 1/4th of the impact has caused by production and end of life treatment of the dielectric fluid. This confirms that hydrocarbon based dielectric fluids makes a significant contribution to the total environmental impact. Hence alternative dielectric fluids such as water based dielectrics (tap water, water mixed with organic compounds and de-ionised water), gas based dielectrics and dry EDM techniques have also been researched[9]. Use of non-hydrocarbon based dielectrics may reduce the potential hazard for the operator health and safety as well. A detailed review of the use of environmental friendly dielectric fluids in EDM[9] reveals that water based dielectrics, alternative to hydrocarbon oil, can be used for die sinking EDM.

Table 1 summarises the research evidence of using alternative dielectric media. The third column compares the performance of alternative dielectrics with conventional hydrocarbon oils. It shows previous research attempts to find the effect of machining performance with alternative dielectric media. Almost all of these studies seem to be primarily motivated to improve the machining performance parameters such as tool wear and material removal rate. Use of alternative dielectric, water or air, with the primary motive of sustainability is hardly evident from the literature. Nevertheless, use of water or air would be a more sustainable option rather than using hydrocarbons oils when the resource extraction and emissions are considered. The environmental savings by using alternative dielectrics are yet to be quantified and compared with that of the conventional hydrocarbon based dielectrics.

Table 1. Alternative dielectric media for EDM

Dielectric medium	Experiment conditions	Machining performance	Ref.
Distilled Water	Work: Ti–6A1–4V (-) Electrode: Cu (+) Pulse duration:.-- Current: 6A	Compared to kerosene: - material removal rate is greater - relative electrode wear ratio is lower	[10]
Distilled water	Work: Low carbon steel (-/+) Electrode: Cu (+/-), Brass (+/-) Pulse duration: 20-500µs Current: 7.5A	Compared to kerosene: - MRR high with brass (-)(but less with cu+) - Surface roughness low with both electrodes - No comparison REW	[5]
Deionised water	Work: Steel Electrode: Brass Pulse duration: 400-1500µs Current:	Compared to hydrocarbon oil: - higher material removal rate - lower electrode wear	[9]
Tap water	Work: Low carbon steel (+) Electrode: Brass (-) Pulse duration: 20-500µs Current: 7.5A	Compared to kerosene: - MRR is high(and higher than distilled water or the mixture too) - Surface roughness is low - No comparison for electrode wear (REW)	[5]
Air	Work: Steel (S45C) Electrode: Cu ø8.6 mm Pulse duration: 350 µs Duty factor 70% 20A, 280V	Compared to oil: - Tool wear ratio is zero - Lower material removal rate.	[11]
Oxygen mixed with water based dielectric fluid (Sodick VITOL-Q-L)	Work: Steel (S45C) Electrode: Cu ø8.6 mm Pulse duration: 350 µs Duty factor 70% 20A, 280V	Compared to oil: - Tool wear ratio is zero - Improved material removal rate.	[12,11]
Nitrogen mixed with water based dielectric fluid (Sodick VITOL-Q-L)	Work: Steel (S45C) Electrode: Cu ø8.6 mm Pulse duration: 350 µs Duty factor 70% 20A, 280V	Not effective	[12]
Argon mixed with water based dielectric fluid (Sodick VITOL-Q-L)	Work: Steel (S45C) Electrode: Cu ø8.6 mm Pulse duration: 350 µs Duty factor 70% 20A, 280V	Not effective	[12]
Helium	Not mentioned as it is only a reference to literature	N/A	[12]

As one of the major role of the dielectric fluid is to flush-off the debris from the machining gap[13], irrespective of type of dielectric is used contamination is unavoidable. For example, if water is used as dielectric then the impact of disposal of used water with contaminants and other process emissions need to be studied. It is ascertained from literature that the reason for the alternative dielectric media to be still unpopular is the superiority of hydrocarbon oils for better machining with less tool wear, high material removal rate and better surface finish compared to alternatives[9] despite improvements in performance are evident.

2.3. Electrochemical machining (ECM)

Electrochemical machining (ECM) is an anodic electrochemical dissolution process using an electrolyte[14]. Common electrolytes used for ECM are dilute (5 - 20%) salt solutions such as sodium nitrate ($NaNO_3$), sodium chloride (NaCl) and sodium chlorate ($NaClO_3$) [15]. However, norm is to use acidic electrolytes like HNO_3 for micro ECM. It has been studied that citric acid can be used as an environmental friendly alternative electrolyte during micro ECM of micro holes and cavities in stainless steel[16]. However, the benefit of using citric acid over other electrolytes on sustainability has not yet been studied and quantified. ECM also creates sludge during machining which might contain harmful contaminants which is yet to be studied. Practical applications of ECM is still limited due to the difficulty of proper tool design, lack of accuracy, and inadequate control of operating parameters[17,18] like inter electrode gap, electrolyte flow rate, pulse duration, etc. Hence, sustainability study of industry scale ECM operation is yet less feasible.

3. Current trends in research

The available publications which explicitly discuss sustainability of UCM practices are then categorised under the type of UCM practice they discuss.

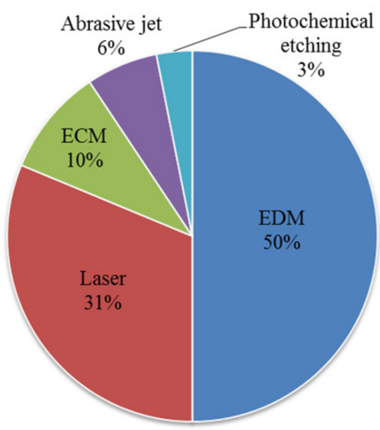

Fig. 6. Types of UCM studied for sustainability

Figure. 6 shows the distribution of types of UCM practices studied mainly in the context of sustainability. Out of 25 total publications some discuss about more than one type of machining methods which leads to a total of 32 entries. As expected 50% of entries were on sustainability studies on EDM shows its popularity. The second 31% is the laser since it is the most widely used UCM which includes CO_2, Nd:YAG laser cutting and sintering types. Only three entries (10%) are concerned on explicit environmental analysis of

ECM which shows a far low amount compared with EDM. The balance 9% entries are on abrasive jet cutting and photochemical etching.

4. Methodologies used for impact assessment

There are several established methods used for analysing the environmental sustainability. Some are designed to assess the life cycle impact of a product from cradle to grave. Some focus on the process level impacts as well. Three such approaches, Eco-Indicator 99, Recipe2008 and CO2PE, are introduced here.

4.1. Eco-indicator99

Eco-indicator99 is the new development of Eco-indicator95 by PRé Consultants Netherland. It is an ‘endpoint’ based indicator which refers to a point at the end of the environmental mechanism[19]. The environmental problems are limited to just three categories which are defined at their endpoint levels[20]. These are damages to,

- Human health
- Ecosystem quality and
- Resources

Eco-indicator follows a top-down approach unlike the bottom-up approach reflected in ISO14040 and ISO 14042 where life cycle inventory (LCIA) is defined to improve the inventory results[20]. LCA starts with a list of all emissions, consumed resources and non-material impacts like land use. As these lists are too lengthier, those are grouped under few impact categories to make it easy to be weighted to get a final result. After weighting the results are interpreted as greenhouse gas effect, ozone depletion, acidification and many others. According to [20], these results are difficult to be interpreted unambiguously. Thus they argue the top-down approach as used in Eco-indicator gives more solid results than bottom-up approach. The final score of eco-indicator99 is expressed as a single indicator called ‘ecopoints’. One ecopoint refers to as one thousandth of the annual environmental load of one average European inhabitant [21].

4.2. ReCiPe2008

The acronym represents the contributing institutions in developing the method. These are the RIVM (National Institute of Public Health and the Environment, Netherlands), Radbound University-Netherlands, CML (Institute of Environmental Sciences, University of Leiden, Netherlands) and PRé Consultants, Netherlands. The principle aim of ReCiPe was to align the midpoint oriented CML method and endpoint based Eco-indicator99 method for LCIAs. The basis of ReCiPe has been the requirement of having a common framework to use both midpoint and endpoint indicators [19]. It contains 18 impact categories at midpoint level and three impact categories at end point level. The method can be used to calculate life cycle impact category indicators in life cycle impact analysis (LCIA).

4.3. CO2PE!

The acronym represents Cooperative Effort on Process Emissions in Manufacturing (CO2PE!). The methodology has been developed with the goal of joining and coordinating international efforts to document, analyse and improve the environmental footprint for a wide range of current and emerging manufacturing processes with respect to their direct and indirect emissions[22]. Improving the LCI data available to high energy consuming unconventional machining is one of the major aims of this method as there is a lack of such data even in the Ecoinvent database, which is a widely referred comprehensive LCI database [22]. The methodology mainly focuses on the actual use phase of the manufacturing process rather theoretical calculations for energy consumptions. The method contains two approaches considering the depth of details. The first is the screening approach where the assessment is made relying on representative publicly available data to calculate energy use, material loss and identifying variables for improvement. The second, in-depth approach contains four modules, a time study, a study of power consumption, a study on consumables and an emission study [22,23]. With those four studies all relevant process inputs and outputs are analysed.

5. Conclusion and further research

Over 120 publications in the area of sustainability of machining processes were reviewed. 90% of those were published after year 2000 and almost 40% of total publications are within the last three years (2010-2013). This shows a positive and increasing trend in sustainability research in machining practices. Out of all the studies it is found that only 25 publications directly or indirectly focus on the issues of sustainability related to UCM processes. Of which almost 70% were published after 2006 signaling a new focus area of research on sustainability. Most widely researched UCM practices are EDM (50%), Laser (31%) and ECM (10%). It can thus be concluded that there is a growing interest towards sustainability of UCM. However there is still a research gap for more quantifiable and integrated study on sustainability of UCM practices. Further research is suggested in bridging this gap.

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